Power Spectra and Auto Correlation Analysis of Hyperfine-induced Long Period Oscillations in the Tunneling Current of Coupled Quantum Dots

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Abstract. We outline power spectra and auto correlation analysis performed on temporal oscillations in the tunneling current of coupled vertical quantum dots. The current is monitored for ~2325 s blocks as the magnetic field is stepped through a high bias feature displaying hysteresis and switching: hallmarks of the hyperfine interaction. Quasi-periodic oscillations of ~2 pA amplitude and of ~100 s period are observed in the current inside the hysteretic feature. Compared to the baseline current outside the hysteretic feature the power spectral density is enhanced by up to three orders of magnitude and the auto correlation displays clear long lived oscillations about zero.

Keywords: Quantum dots, Hyperfine interaction, Nuclear spin

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INTRODUCTION

In recent years the influence of nuclei on electrons confined in III-V semiconductor based quantum dot transistors has attracted interest [1,2]. In the seminal work of Ono and Tarucha, one of the most interesting observations was nuclear-spin-induced oscillations in the leakage current of a spin-blockaded weakly-coupled vertical double quantum dot device [3]. The oscillations were highly regular in time with a period reaching ~100 s. A clear understanding of these oscillations is still lacking. Some theoretical investigations of localized spin in a nuclear environment revealed temporal oscillations in calculated correlation functions or calculated current, however, the form of the oscillations was found to be very dependent on the choice of input parameters and the period of the oscillations typically was found to be sub-second [4,5].

More recently, irregular fluctuations in the current in lateral double quantum dot devices due to nuclear spin dynamics have been observed, and the power spectra evaluated revealed a 1/f-like noise dependence in frequency f [6,7]. For a related spin problem, limit-cycles and chaos in the current through a quantum dot have been theoretically investigated [8].

Here, we report on the properties of the power spectrum and autocorrelation function for temporal current oscillations seen outside of the familiar spin-blockade regime in a weakly-coupled vertical double quantum dot device and attributed to hyperfine interaction [9].

EXPERIMENT

At constant bias (-12 mV) and gate voltage (-1.22 V), the magnetic (B-) field applied parallel to the current was stepped from 3.94 to 3.99 T in 2 mT increments through the feature of interest and the current captured for 2325 s at each B-field [see Ref. 9 for more details and the hysteretic behavior observed on sweeping the B-field up and down.]. Figure 1 (a) shows two current vs. time traces: one is taken from inside the feature (trace A) and the other from outside (trace B). The current captured for all twenty-six traces is presented as a histogram in Fig. 1 (b).

The current oscillations with ~2 pA amplitude in trace A are intermediate in nature between those described in Ref. 3 and Refs. 6-7, namely they are quasi-periodic and seemingly with strong long (~100 s) period component and weaker shorter period components. The character of the oscillations changes systematically as the B-field is stepped through a ~50 mT range. When the current is maximally oscillating there is a clear double-peak distribution in the current [the peaks are labeled “high” and “low” in Fig. 1 (b)]. Note the baseline current (in trace B for example) instead gives a very sharp single-peak distribution with full width at half maximum ~100 fA (representing intrinsic noise of the measurement set-up).
Relative to the power spectral density for the baseline current (trace B for example), when the current oscillates (trace A for example), we observe a clear elevation in spectral weight for all frequencies below ~1 Hz [see Fig. 2 (a)], a 1/f^n dependence with exponent n≈2 in the range 0.01 to 1 Hz before a flatter response below 0.01 Hz with some pronounced spectral peaks near 0.01 Hz. Note the power spectral density of trace A is enhanced by up to three orders of magnitude near ~0.01 Hz over that for trace B (which has a 1/f^{1.5} dependence over nearly the entire frequency range shown).

Figure 2 (b) reveals clear and long lived oscillations around zero in the auto correlation function (ACF) with maxima spaced by ~125 s for trace A (consistent with the largest peak in the power spectrum near 80 mHz). In contrast, the correlation magnitude for trace B is orders of magnitude weaker.

Summarizing, with increasing B-field the tunneling current is suppressed before settling into a bimodal state with long period oscillations, likely due to the coupling of a many-body spin state to the fluctuating nuclear bath, leading to a strong signature in terms of the power spectrum and auto correlation. Due to the different B-field orientation, nuclear magnetic resonance (NMR) measurements like those reported in Ref. 3 were not performed. NMR did not explain why the current oscillations in Ref. 3 had ~100 s period or were so regular, nor was NMR reported in Refs. 6-7.

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**REFERENCES**